Challenges to Ultra-thin Resist Process for LEEPL

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An ultra-thin resist process is indispensable for low-energy electron-beam proximity projection lithography (LEEPL) because it uses 2-kV-accelerated electrons with small penetration depth. 70-nm-thick chemically-amplified resists for a tri-layer process were developed with the consideration of the interaction of a polymer with a spin-on-glass material, showing the resolution of 140-nm-pitch contact holes. Application of the tri-layer process developed for LEEPL to making via holes in a 90-nm-node back-end-of-line process proved that the ultra-thin resist was lithographically useful in terms of resolution and etching tolerance. Exploring the resolution performance of electron beam lithography showed that line edge roughness and resolution limit of resist patterns was in linear relation with blur of latent image profile. Reducing the resist thickness is effective in enhancing the resolution of LEEPL because 47 % of the blur is attributed to electron scattering. A Monte Carlo simulation shows that the blur caused by the electron scattering decreases 41 %, to 20 nm from 34 nm, by reducing the resist thickness to 30 nm from 70 nm.

Keywords: LEEPL, NGL, ultra-thin resist

1. Introduction

Understanding the properties of a highly interfacial resist film has been an active area of research in semiconductor microlithography that using ultra-thin resists less than 100-nm thick is considered as a way to offset optical absorption, improve depth of focus, and mitigate pattern collapse associated with high aspect ratio. The properties of polymeric systems such as glass-transition temperature (Tg) become significantly altered from their bulk quantities as the film thickness approaches the dimensions of the macromolecule because of the interaction of a polymer with a substrate.1,3

Low-energy electron-beam proximity projection lithography (LEEPL) was proposed for manufacturing 65-nm-node devices. The LEEPL concept is based on a 2-kV-accelerated e-beam with a 1x stencil mask. An electron gun with a LaB6 source and a condenser lens form a collimated e-beam of about 500 μm diameter. The e-beam scans the 1x mask and a patterned image of the mask plane is transferred to a resist film in 50 μm proximity to the mask. An ultra-thin resist process is indispensable for LEEPL because it uses low-energy electrons with small penetration depth.

Among the candidates for the next-generation lithography, LEEPL seems to be the only tool which will be available in time for the 65-nm-node device mass production.3 A sufficient process margin for contact holes has not been obtained by optical lithography,6,7 even though efforts have been made to prolong the optical lithography by using a high numerical aperture lens and resolution-enhancement techniques including optical proximity correction, off-axis illumination, and phase-shift masks.

In this study, 70-nm-thick chemically-amplified resists for a tri-layer process were developed with the consideration of the interaction of a polymer with a spin-on-glass material, which was typical of the ultra-thin resist sensitive to acid diffusivity and
hydrophilicity of the underlying layer. Applying the tri-layer resist process developed to fabricating via holes in a 90-nm-node back-end-of-line (BEOL) process proved that the process developed for LEEPL was compatible with a conventional process using an ArF scanner. Exploring the resolution performance of various electron beam lithography including 100-keV electron projection lithography, 50-keV variable-shaped and Gaussian e-beam lithography, and 2-keV LEEPL showed that line edge roughness and resolution limit of resist patterns was in linear relation with blur of latent image profile supposing the line spread function to be Gaussian. It is shown that reducing the resist thickness to 30 nm is effective in enhancing the resolution of LEEPL to patterning 90-nm-pitch contact holes required by the 45-nm-node device manufacturing.

2. Resolution properties of the ultra-thin resist

To characterize the resolution properties of the ultra-thin resist, a conventional variable-shaped e-beam direct writer, HL-800D (Hitachi), was used to expose a negative-type chemically-amplified resist, NEB22 (Sumitomo Chemical), on Si substrates. Line edge roughness (LER) was measured by a critical-dimension scanning-electron microscope (CD-SEM), S-9220 (Hitachi), with a threshold level of 50%. The LER was considered to be 3σ of the pattern edge locations of 32 sections.

Figure 1 shows the LER of 100-nm-width lines and spaces patterns as a function of the pre-baking temperature with the resist thickness of 250 nm and 70 nm. The 70-nm-thick resist was prepared by diluting the resist dedicated for the use with 250 nm thick with a solvent. The duration of the pre-baking and the post-exposure baking condition were 120 sec and 120 sec at 100 °C. Note that reducing the resist thickness to 70 nm from 250 nm raised the minimum LER with the shift of the optimal pre-baking temperature.

This is probably because the properties of the polymeric systems such as Tg become significantly altered from their bulk quantities as the film thickness approaches the dimension of the macromolecule. For example, it is reported that Tg can decrease, increase, or remain constant when the film thickness approaches a few multiples of the polymer scale, with shifts as great as ±50 °C. Fryers et al. concluded that the nature of the interaction of the polymer with the substrate is the dominant factor in determining dimension-dependent Tg. Figure 2 shows the optimum exposure dose for the 100-nm isolated line (Eopt) as

![Fig. 1. Line edge roughness as a function of the pre-baking temperature depending on the resist thickness.](image1)

![Fig. 2. Optimum exposure dose as a function of the pre-baking temperature depending on the resist thickness.](image2)
a function of the pre-baking temperature. The pre-baking temperature at which $E_{\text{opt}}$ increased rapidly was 20 °C lower for the 70-nm-thick film, suggesting the decrease of $T_\theta$ with the film thickness.

Residual solvent acting as an acid diffusion path is a concern with the thin-film characteristics as well as a thickness-dependent concentration of a photo-acid generator. To obtain a thinner film by spin coating, resist viscosity has to be lowered by diluting with a solvent. Excess solvent volatilizes during the pre-baking and appropriate quantity remains in the film as the residual solvent. In the context of the same pre-baking condition, content of the residual solvent in a thin film will be lower than that in a thick film because the solvent volatilizes from the film surface.

Another possible cause of the thin-film phenomena is a polymer chain orientation in thin resist. The ellipsoidal nature of each molecule is largely accommodated within highly confined films by orientating its long axis parallel to the surface. It is reasonable to say that the chain orientation affects direction and length of the acid diffusion because the acid diffuses through periphery of the polymer chain.

Selection of the spin-on-glass material which works well with the resist material used is critical to have good resolution in the ultra-thin resist tri-layer process as shown in Fig. 3. Imaging resist/spin-on-glass/underlying layer of 70/70/300 nm in thickness was used. A LEEPL-β tool with a beam current about 5 μA projected mask patterns on the positive-type chemically-amplified resists. Resist sensitivities were from 1.5 through 2.5 μC/cm² depending on the resist and the underlying layer. The upper micrographs in Fig. 3 are the resist patterns of 160-nm-pitch contact holes on a Si substrate. The fluctuation in size, the connection between holes, and where holes have disappeared can be seen. The resolution was improved by selecting an appropriate spin-on-glass as shown in the lower micrographs. 140-nm-pitch dense patterns were obtained by using the tri-layer process developed as shown in Fig. 4.

Fig. 3. Scanning-electron micrographs of 160-nm-pitch contact holes. The underlying layer was Si (upper) and a spin-on-glass (lower).

Fig. 4. Scanning-electron micrographs of 140-nm-pitch contact holes.
3. Application of the 70-nm-thick resist

Practicality of the 70-nm-thick resist for LEEPL was examined by applying to fabrication of the via holes in a 90-nm-node BEOL process.\(^\text{13}\)

A first metal layer was made by using an ArF scanner and a LEEPL mask aligned to it to make a second via-hole layer. Following the etching of the spin-on-glass layer (Fig. 5(a)), the patterns were transferred to the bottom-layer resist (Fig. 5(b)). The underlying SiO\(_2\) and a low-k material was etched as shown in Fig. 5(c). Figure 5(d) shows the cross section of a via hole made by using the ArF scanner. The shape of the via hole is almost identical, showing that the LEEPL tri-layer resist process is compatible with the ArF process.

The second metal layer was patterned by the ArF scanner and the via holes were filled with tungsten and copper. The electrical resistances of a via hole made by ArF and LEEPL were almost the same and nominal in the diameters between 130 nm and 190 nm. The electrical resistance of the via hole made by LEEPL increased to 4 Ω from 2 Ω with decreasing the diameter to 100 nm from 130 nm, while the smallest via hole achievable with the ArF scanner was 130 nm.

4. Motivation for 30-nm-thick resists

To quantify impact of thinning the resist on the LEEPL process, the resolution performance of various electron beam lithography including the 100-keV electron projection lithography proof-of-concept column, EPL-POC\(^\text{14}\) (Nikon), a 50-keV Gaussian e-beam writer, JBX-5FE (JEOL), a 50-keV variable-shaped e-beam writer, HL-800D (Hitachi), 2-keV LEEPL proof-of-concept column, LEEPL-\(\alpha\) (LEEPL), and 2-keV LEEPL-\(\beta\) (Accretech) were explored by using chemically-amplified resists (NEB22, NEB31, CAR-A\(^\text{15}\), CAR-B\(^\text{15}\)) developed by TMAH 2.38 % and the non-chemically-amplified resists (ZEP520, PMMA, Calixarene\(^\text{16}\)) developed by xylene.

Figure 6 shows the LER of a 100-nm-isolated line as a function of the blur of the latent image profile defined by Eq. (1),

\[
QBP(\sigma_{\text{QIP}}, x) = \frac{D}{\sigma_{\text{QIP}} \sqrt{\pi}} \int_{0}^{w} \exp\left(-\frac{(x - y)^2}{2\sigma_{\text{QIP}}^2}\right) dy
\]

where \(D\) is the exposure dose, \(W\) is the designed width, and \(\sigma_{\text{QIP}}\) is the blur of the latent image profile including the acid diffusion and the blur caused by the electron scattering. Reducing the blur is essential for the projection lithography (EPL-POC, HL-800D, LEEPL) to decrease the LER, even though the LER at a blur below 30 nm...
was limited to about 2 nm.\textsuperscript{17}

Figure 7 shows the resolution limit of an isolated line with the exposure latitude about 2\% and lines and spaces patterns with the exposure latitude about 10\% as a function of the blur in LEEPL. The exposure latitude is a CD±10\% margin of the exposure dose. Patterns presenting collapse, division, residuals, or height-reduction were considered to be unresolved patterns. The resolution was in linear relation to the blur, while the resolution of the dense patterns was limited to 70 nm because of the resolution limit of the mask pattern. The blur of 30 nm is necessary for 45 nm 1:1 patterns, required by the 45-nm node, with exposure latitude of 10\% when corresponding stencil masks become available.

Reducing the blur of the latent image profile has a positive impact on the resolution and the LER. The quantitative analysis of the blur of LEEPL in our previous work showed that 47\% of the blur, 34 nm, was attributed to the scattering of 2-keV electrons in the 70-nm-thick resist film,\textsuperscript{18} which means that increasing electron energy and/or thinning the resist is the most effective in decreasing the blur. Figure 8 shows the quantitative influence of reducing the resist thickness to 30 nm from 70 nm on improving the blur. It is calculated by using a Monte Carlo simulation that the blur caused by the electron scattering is reduced 41\%, to 20 nm from 34 nm. The blur of the latent image profile including electron-optical blur and the acid diffusion is reduced to 41 nm from 49 nm by using the 30-nm-thick resist. The blur of 30 nm required by the 45-nm node is achievable by using the 30-nm-thick resist.

![Fig. 7. Resolution as a function of the blur of the latent image profile in LEEPL.](image)

![Fig. 8. Quantitative influence of reducing the resist thickness to 30 nm from 70 nm on improving the blur of the latent image profile.](image)
resist with the electron-optical blur of 8 nm and the acid diffusion of 18 nm.

5. Conclusions
The resolution properties of the 70 and 250-nm-thick negative-type chemically-amplified resist were compared by using the 50-keV variable-shaped e-beam writer. The optimum pre-baking temperature decreased 20 °C by reducing the resist thickness. The 70-nm-thick positive-tone chemically-amplified resists were developed for the tri-layer process of LEEPL with the consideration of the interaction of the polymer with the spin-on-glass material. The via holes in the 90-nm-node BEOL process were fabricated by using the tri-layer process developed, showing that the electrical resistances of the via hole made by ArF and LEEPL were the same in the diameter between 130 and 190 nm. Exploring the resolution performance of the electron beam lithography including the 100-keV electron projection lithography showed that the LER and the resolution limit was in linear relation with the blur of the latent image profile. It was calculated by using a Monte Carlo simulation that the blur caused by the electron scattering decreased 41 %, to 20 from 34 nm, by reducing the resist thickness to 30 from 70 nm. The blur of 30 nm required by the 45-nm node is achievable by using the 30-nm-thick resist with the electron-optical blur of 8 nm and the acid diffusion of 18 nm.

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References
15. Positive-type chemically-amplified resists exclusively developed for low-energy electron-beam lithography.